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Temperature Hierarchy Computation of Steel Columns Exposed to Red-heat Furnace Charge in Safety Pit

ZHANG Can[a], WANG Ya-jun[b,*]

[a]*China People's Armed Police Forces Academy,Langfang,China*
[b] *Lanzhou University,Lanzhou,China*

Abstract

For evaluating the fire-resistance stability of steel columns exposed to a red-heat furnace charge in safety pit in a nonferrous metal factory workshop, the temperature distribution of steel columns within the height of 10m is calculated by a hierarchy computing method based on heat radiation theories and heat transfer between the flange plate and the web plate. The numerical calculation result indicates that there are great differences between the temperature of the web plate and the flange plate. The influences of the height of the flange plate and the relative position between furnace charge and steel columns on the thermal are analyzed. The results offer some references for the Performance-Based Fire Protection Design of the nonferrous metal factory workshop.

Keywords:metal factory; steel columns, radioactive, temperature distribution

1. Introduction

During a nonferrous metallurgical process, the charging would be put in a safety pit when an accident happened. The furnace temperature may be up to 1000 or more. Although protective measures were adopted to avoid a direct contact with a steel column, the strong radiation has a potential to damage the stability of the steel columns. Therefore it is important to study the temperature distribution of a steel column exposed to a red-heat furnace charge in safety pit in a nonferrous metal factory workshop.

A numerical method was used in [1] to calculate the temperature distribution of the flange near to the furnace change. Despite its relative simplicity, it didn't take the energy balance of the flange and the back web into account, the total temperature distribution remains absent.

In this paper, we proposed a Hierarchy Computation which divided a steel I-section into three sections: the front flange, the web and the back flange. Using a numerical method, the temperature distribution is obtained.

* Corresponding author. Tel.:+86-13931665453
E-mail address: beauty_can@126.com.

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Nomenclature

d	flange thickness of an I-section(mm)
b_f	flange width of an I-section(mm)
b'	web height of an I-section(mm)
τ	web thickness of I-section(mm)
w	width of a furnace charge(m)
L	length of a furnace charge(m)
h	height of a furnace charge(m)
s	distance between a furnace charge and an I-section(m)
t	time
c_s	capacity of an I-section
T_f	temperature of furnace charge($^\circ$C)
T_{sI}	front flange temperature($^\circ$C)
ΔT_{sI}	front flange temperature increment($^\circ$C)
T_{sM}	web temperature of an I-section($^\circ$C)
ΔT_{sM}	web temperature increment($^\circ$C)
T_{sB}	back flange temperature of an I-section ($^\circ$C)
ΔT_{sB}	back flange temperature increment($^\circ$C)
T_s'	steel temperature of an I-section($^\circ$C) at time $t-\Delta t$
T_0	ambient temperature($^\circ$C)
x, y, z	space coordinates in Cartesian system
Δt	time increment
TI	maximum temperature of the front flange at time t($^\circ$C)
TM	maximum temperature of web ($^\circ$C)
TB	maximum temperature of the back flange ($^\circ$C)
i, j	denotes nodal positions in numerical solution

Greek letters

η	scale factor
ρ	density(kg/m^3)
ρ_s	density of an I-section(kg/m^3)

Subscripts

s	steel
sI	front flange of an I-section near to a furnace charge
sM	web of an I-section
sB	back flange of an I-section

2. Temperature computation

2.1. . Numerical models of a steel I-section

The structural model for numerical computation is shown in Fig.1, in which a heated steel column is divided into three sections: the front flange, the web and the back flange. Note here we assumed temperature inside each parts of the steel I-section is uniform and equal to the surface temperature, due to high thermal conductivity.

In Fig. 1, b_f (mm) is the flange width of an I-section, d (mm) is the flange thickness of an I-section, b' (mm) is the web height of an I-section, τ (mm) is the web thickness of I-section, w (m) is the width of a furnace charge, L (m) is the length of a furnace charge, s (m) is the distance between a furnace charge and an I-section, η is the ratio of the distance from the axis of the steel columns and the length of the furnace charge, ranging from 0 to 0.5. the surface of the furnace charge is also divided into two areas: area Ⅰ, Ⅳ is the radioactive surface to the web and Ⅱ，Ⅲ is the radioactive surface to the back flange.

The schematic of a steel I-section exposed to a furnace charge is shown in Fig. 2. It consists of five facets: two surfaces of the front flange, one surface of the web and two surfaces of the back flange, with numbering shown in the figure

2.2. Formulation of radiation energy balance of the steel columns

The following column and furnace charge design parameters are identified to influence the temperature of the steel columns: the surface width of the furnace charge, the web thickness, the web width, the distance between the steel columns and the furnace charge, i.e. the meshing division of the surface of the furnace charge is shown in Fig. 3.consider the steel column that is divided into equal increments of 0.5mm in the z direction.

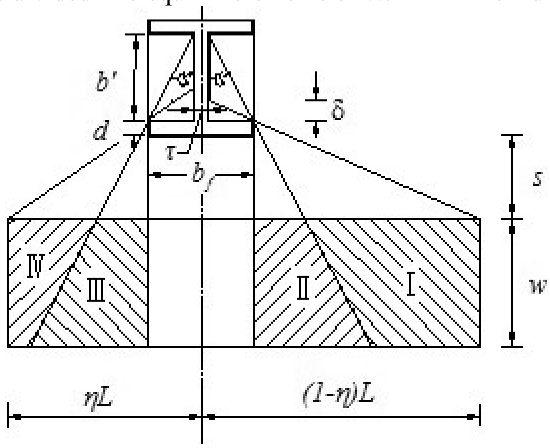

Fig.1. a steel I-section and a furnace charge model

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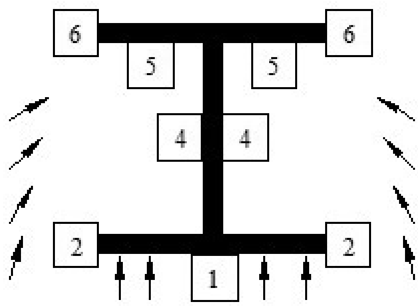

Fig. 2. Schematic of the radioactive heat transfer model for a steel I-section

In an earlier work [1], in the steel columns, the net radioactive heat is associated with two factors, namely the total incoming $q_1(J)$ and $q_2(J)$, the total emitted $q_3(J)$. For each factor:

$$q_1 = \sum_{w}\sum_{L} 5.67 \times 0.66 \times 0.8 \Delta x \Delta y \Delta t \cdot \frac{0.5 b_f z x_1}{\pi (x_1^2 + y_1^2 + z^2)^2} \left(\frac{T_f + 273}{100}\right)^4 \quad (1)$$

$$q_2 = \sum_{w}\sum_{L-b_f} 5.67 \times 0.66 \times 0.8 \Delta x \Delta y \Delta t \cdot \frac{d z x_1}{\pi (x_1^2 + y_1^2 + z^2)^2} \left(\frac{T_f + 273}{100}\right)^4 \quad (2)$$

$$q_3 = 0.8 \times 5.67 \times 2 \times 0.5 \times \Delta t \times (b_f + d) \left(\frac{T_s' + 273}{100}\right)^4 \quad (3)$$

Within a sufficiently small time step Δt such that quasi-state can be achieved, the temperature increment of the front flange can be calculated by:

$$\Delta T_{sI} = \frac{q_1 + q_2 - q_3}{0.5 c_s \rho_s d b_f} \tag{4}$$

From Eq. (4), the temperature of the front flange at time t is given by:

$$T_{sI} = T_0 + \sum_{1}^{t/\Delta t} \Delta T_{sI} \tag{5}$$

The definition of the parameters referred in above expresses can be found in [1].

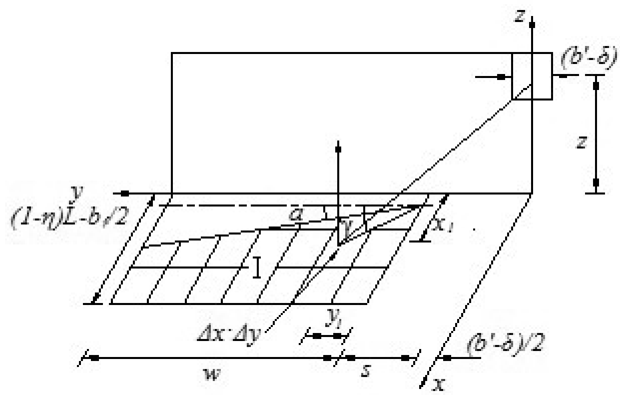

Fig. 3. Heat transfer between the surface of the furnace charge and the web

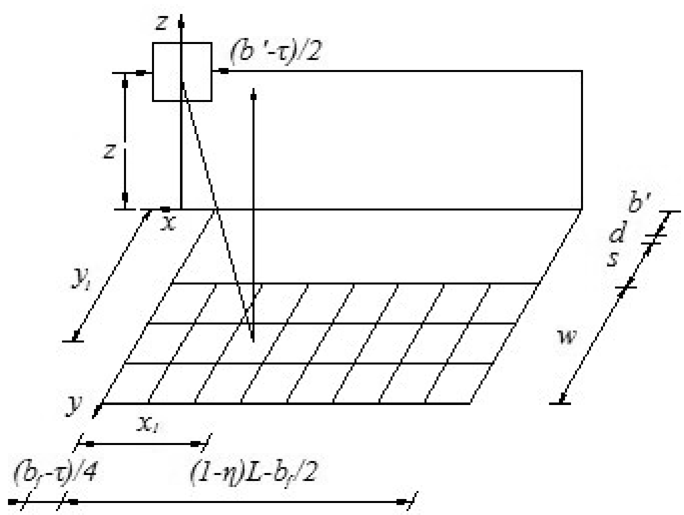

Fig. 4. Heat transfer between the surface of the furnace charge and the grain side of the back flange

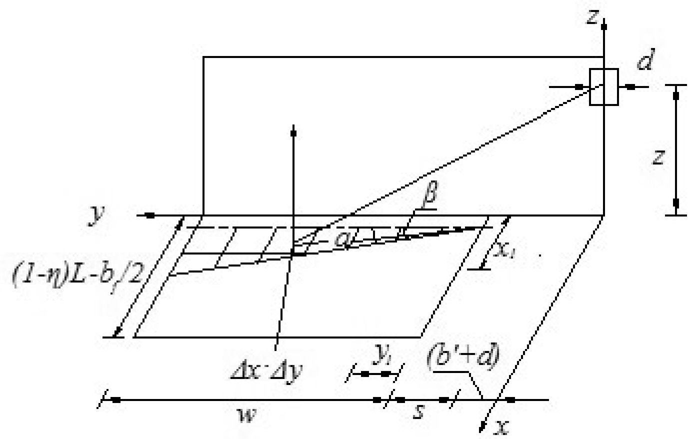

Fig. 5. Heat transfer between the surface of the furnace charge and one side of the back flange

Fig.3, fig. 4, fig. 5 display models of each part of the steel I-section exposed to the furnace charge. In case fig. 3, according to Heat Transfer [2], the radioactive heat of the web $q_4(J)$ is written as:

$$q_4 = \sum_{I+IV} 5.67\times 0.66\times 0.8\Delta x\Delta y\Delta t\cdot\frac{0.5(b'-\tau)zx_1}{\pi(x_1^2+y_1^2+z^2)^2}(\frac{T_f+273}{100})^4 \tag{6}$$

Based on the same way, the absorb heat by the back flange can be expressed as:

$$q_5 = \sum_{W}\sum_{L-b_f} 5.67\times 0.66\times 0.8\Delta x\Delta y\Delta t\cdot\frac{0.5(b'-\delta)zx_1}{\pi(x_1^2+y_1^2+z^2)^2}(\frac{T_f+273}{100})^4 \tag{7}$$

$$q_6 = \sum_{II+III} 5.67\times 0.66\times 0.8\Delta x\Delta y\Delta t\cdot\frac{dzx_1}{\pi(x_1^2+y_1^2+z^2)^2}(\frac{T_f+273}{100})^4 \tag{8}$$

Where T_f denotes the temperature of the furnace charge, it is given by [1] as:

$$T_f = \begin{cases} 1250 & \mathrm{Re} > 0 \\ 1250 - 0.66\times 5.67\times 10^{-8}\Delta t(w+2h)\cdot(l+2h)(T_f'+273)^4 & \mathrm{Re} < 0 \end{cases} \tag{9}$$

$$\mathrm{Re} = 251000wLh\rho - 0.66\times 5.67\times 10^{-8}\Delta t(w+2h)\cdot(L+2h)(T_f'+273)^4 \tag{10}$$

Where L is the length of the furnace charge, w is the width of the furnace charge, h is the height of the furnace charge.

The steel column also emits heat by radiation itself, the exposed area of the web is $2\times b'$, according to the radiation law this heat $q_7(J)$ may be expressed as:

$$q_7 = 0.8\times 5.67\times 2\times 0.5\times\Delta t\times b'(\frac{T_s'+273}{100})^4 \tag{11}$$

Where T_s' is the flange temperature at $t-\Delta t$ time. Based on the same way, the emitted heat of the back flange $q_8(J)$ can be obtained as:

$$q_8 = 0.8\times5.67\times0.5\times\Delta t\times(b_f-\tau+2\times d)(\frac{T_s'+273}{100})^4 \tag{12}$$

According to the conversation of energy, the growth of the web temperature ΔT_{sM} ($^\circ$C) and the growth of the back flange temperature ΔT_{sB} ($^\circ$C) are calculated using the following equations:

$$\Delta T_{sM} = \frac{q_4-q_7}{0.5c_s\rho_s(b'-\delta)\tau} \tag{13}$$

$$\Delta T_{sB} = \frac{q_5+q_6-q_8}{0.5c_s\rho_s db_f} \tag{14}$$

Using Eqs. (13) and (14), we have the web temperature T_{sM} ($^\circ$C) and the back flange temperature T_{sB} ($^\circ$C):

$$T_{sM} = T_0 + \sum_{1}^{t/\Delta t} T_{sM} \tag{15}$$

$$T_{sB} = T_0 + \sum_{1}^{t/\Delta t} \Delta T_{sB} \tag{16}$$

Where T_0 is 30°C.

In above sections, we assumed heat insulation between the web and the flange to calculate the temperature. Put the heat transfer between them into account, the heat transfer difference equation in unsteady-state condition was formulated:

$$T_{sk}(i,j,t+\Delta t) = \frac{\lambda_s\Delta t}{c_s(t)\rho_s}\left[T_s(i+1,j,t)+T_s(i-1,j,t)-2T_s(i,j,t)\right]+T_s(i,j,t)(k=I,M,B) \tag{17}$$

Consider the heat transfer in the axis direction, the temperature is expressed by:

$$T_S(i,j,t+\Delta t) = \frac{\lambda_S\Delta t}{c_S(t)\rho_S}\left[T_S(i,j+1,t)+T_S(i,j-1,t)-2T_S(i,j,t)\right]+T_S(i,j,t)(k=I,M,B) \tag{18}$$

The temperature distribution of the steel columns is obtained by using the numerical calculation above. Results are discussed in the following sections.

3. Results of temperature hierarchy computation of a steel column

Table 1 lists all parameters used in the calculation. Simulation results using these parameters are shown in table 2, where TI, TM, TB represent the maximum temperature of the front flange, the web and the back flange.

It can be seen that the surface width of the furnace charge and the relative position of the furnace charge and the steel columns have a significant influence on the temperature of the steel column. As the width of the furnace charge continues to increase to values above 10m or decrease to values below 3m, the change of the temperature has ceased.

Table 1. Case studied

Parameter	Values
z	0.25,0.75,1.25,1.75,2.25,2.75,3.25,3.75,4.25,4.75,5.25,5.75,6.25,6.75,7.25,7.75,8.25,8.75,9.25,9.75
w	3,4.2,5.4,6.6, 7.8,9,10
η	0.5,0.3,0.0
s	0.5,1.0,1.5,2.0
L	9
d	25

Table 2. Maximum temperature of each section of the steel column

η	0.5			1.0			1.5			2.0			*w/m*
	TI	TM	TB	TI	TM	TB	TI	TM	TB	TI	TM	TB	
0.5	510	385	286	440	326	237	386	273	199	341	228	167	≤3
	539	407	296	474	350	249	422	295	210	377	250	178	4.2
	561	425	306	501	366	258	453	313	221	410	266	188	5.4
	575	435	312	520	377	267	474	325	228	433	278	196	6.6
	586	442	316	532	385	272	489	332	235	450	286	202	7.8
	595	446	322	543	390	277	500	336	239	463	292	206	9
	600	449	325	550	392	280	507	341	242	470	295	209	≥10
0.3	505	376	280	432	313	233	375	260	195	331	217	165	≤3
	533	393	291	465	335	245	411	282	208	366	238	178	4.2
	555	410	301	492	352	256	441	299	220	398	256	190	5.4
	569	420	309	510	363	265	462	311	230	421	267	200	6.6
	577	427	315	522	370	272	477	319	237	438	275	208	7.8
	585	432	321	531	376	278	488	325	244	450	281	213	9
	590	434	325	538	379	283	495	329	248	458	285	220	≥10
0.0	382	303	251	328	262	211	289	228	182	257	199	157	≤3
	407	325	266	358	285	227	321	251	198	291	222	174	4.2
	428	344	280	383	306	242	349	272	214	320	242	190	5.4
	443	358	291	402	320	255	369	287	226	342	258	203	6.6
	456	368	301	418	331	265	386	298	237	358	270	213	7.8
	466	376	309	429	339	274	400	306	246	373	277	222	9
	472	380	314	437	344	280	408	312	252	383	285	230	≥10

Note:

1. The data in table 2 can be interpolated linearly.

Table 3 shows the web height has a significant influence on its temperature. The bigger of the web height, the higher of its temperature is. As the height increases, the speed of heat loss grows faster than the speed of the heat absorption. We can see this change tend from Fig.5

Table 3. Maximum temperature of the web

η	b^f/mm							*s/m*
	0.3	0.36	0.4	0.45	0.5	0.56	0.63	
0.5	480	475	476	450	435	416	395	0.5
	435	418	410	393	376	359	338	1.0
	374	364	350	340	325	307	292	1.5
	324	313	301	292	278	267	250	2.0

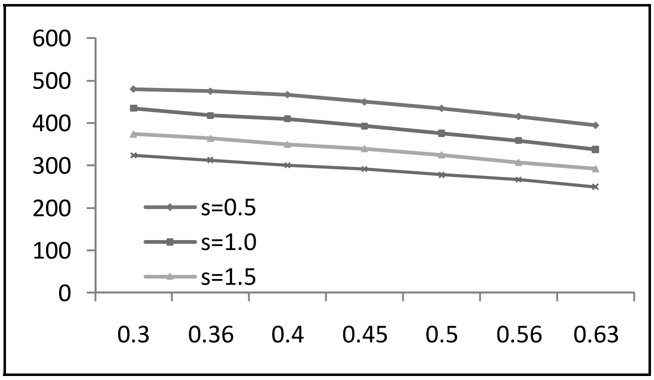

Fig 5 web temperature: influence of thickness

It was pointed out in table 4 and Fig. 6, this temperature decreases with the increases of the web thickness. It may be due to the capacity becomes greater as the thickness increases.

Table 4. Maximum temperature of the web at $s = 1.0, \eta = 0.5$

w/m	τ/m						
	0.045	0.054	0.01	0.0125	0.015	0.02	0.025
4.2	389	386	371	365	361	354	348
6.6	404	403	396	392	388	382	377

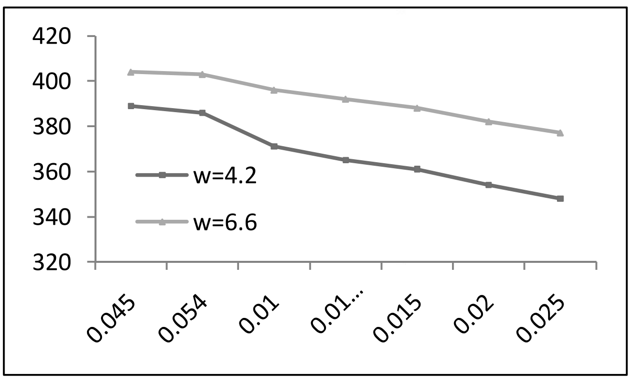

Fig 6 web temperature: influence of width

4. Conclusions

This paper presented a numerical study on the temperature of an I-section exposed to a furnace charge using a method of hierarchy computation. In this way, the temperature distribution of an I-section is gained. The temperature of the front flange is the biggest and the temperature of the back flange is the smallest. The thickness and width of the web have a significant influence on its temperature. Because of the differences in the temperature of each parts of the steel, the temperature moment should be put into account in the performance-based fire protection design of the nonferrous metal factory workshop.

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Reference

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